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A KNOWLEDGE-BASED SYSTEM TO AID SELECTION OF EXCAVATING EQUIPMENT

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A KNOWLEDGE-BASED SYSTEM TO AID SELECTION OF EXCAVATING EQUIPMENT

UN SYSTÈME À BASE DE CONNAISSANCES POUR AIDER LE SELECTIONNEMENT D'ÉQUIPEMENT POUR CREUSER

J. Hadjigeorgiou
McGill University

Technical Report

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ABSTRACT

This report describes a knowledge-based system to aid in the selection of types of excavating equipment for use at construction sites and in open-pit mines. The system considers only the impact of certain geotechnical properties of the material to be excavated on equipment selection decisions. It was developed using a PROLOG-based inference engine.

RÉSUMÉ

Le présent rapport decrit un système à base de connaissance pour aider le processer de selectionnement d'équipment pour creuser tels qu'utilisés dans les domaines de construction et de mines à ciel ouvertes. Le choix est basé sur les attributs géotechniques du matériel à creuser. Le système utilise le langage PROLOG.

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A KNOWLEDGE-BASED SYSTEM TO AID SELECTION OF EXCAVATING EQUIPMENT

1.0 INTRODUCTION

The Systems Laboratory is carrying out research on resource industry applications of decision support systems. This work encompasses different computer-based technologies inc] ding modelling and knowledge-based systems and various resource industry sectors including mining, (Chan 1982), (Nenonen et al. 1988). This report describes development of a prototype of a knowledge-based system to assist in the selection of excavation equipment for surface mining and construction.

Mine planning involves many interdependent site-specific and economic conditions. One of the decisions to be made during mine design is the selection of the mining equipment. This selection is made during the early stages of mine design when knowledge of ground conditions is limited. Geological conditions have a strong impact on the choice of the method of mining and on capital and operating expenditures. Regarding excavation, the main decision is whether to blast or rip the material, a decision that significantly influences the costs of the excavating operation. In some cases, environmental constraints can limit or eliminate the blasting option. Therefore, it is imperative to define an appropriate means of characterizing the rock mass for excavation purposes, as a basis for selecting the equipment and the associated method of excavation. This process is also important in determining whether contractual obligations relating to the method of earth moving for civil engineering excavations are being met.

At present, there is no comprehensive engineering system available that can guide the construction contractor or mine operator in equipment selection. Such a system should be based on knowledge acquired through experience and on knowledge from several engineering disciplines. The selected equipment must have the productive capacity to meet the construction or mining schedules at the lowest projected unit cost. Furthermore, initial capital outlays should be kept at such levels to enhance the project appeal.

This report outlines work in the Systems Laboratory of the Division of Mechanical Engineering on development of a knowledge-based system to assist in selection of surface excavation equipment. It provides an overview of the selection process and focuses on the geotechnical parameters influencing equipment performance and selection. This system will form part of a comprehensive equipment selection system that will account for other factors and will utilize other computer-based technologies including simulation and optimisation.

2.0 EXCAVATING TECHNIQUES

Excavation concerns moving soil or rock, the basic distinction being that blasting is required to break rock for excavation but is not required in the case of soil. Earth moving involves several operations:

(a) Material Loosening
(b) Digging
(c) Loading
(d) Transporting
(e) Dumping

While limited preparation is required for digging soil type material it is common practice to fragment rock-type material using explosives. The development of more poverful equipment has made it possible to operate in what has traditionally been categorised as difficult digging conditions, without extensive ground preparation. This has led to the possibility of increased economic benefits in the form of productivity gains and lower blasting costs. Consequently, there has been a reneved interest in excavation technology and methodology.

Intact rock or highly consolidated earth material can sometimes be efficiently loosened by ripping. This process is a variation of the ploughing techniques employed for centuries by farmers. The geological origin of the rock can provide a useful indication of the rippability of the material. For example, "sedimentary" rocks feature stratification and cleavage planes, making them more amenable to ripping than "igneous" rocks. Metamorphic rocks are rippable to varying degrees. The recent popularity of rippers arises from advances in tractor and ripper design resulting in increased pover and force generation. It has become possible to rip in conditions where blasting used to be the only alternative.

Blasting has traditionally been used to loosen intact rock material and hard material lenses. However, it is also being used in diggable material, on the basis that increased fragmentation prolongs the life of excavating equipment.

This report concerns the selection of earthmoving equipment in environments not requiring blasting. Therefore, a reviev of blasting operations is beyond the scope of this work.

3.0 TYPES OF EXCAVATING EQUIPMENT

3.1 Scrapers

Earthmoving scrapers are designed for both loading and hauling operations. The basic components of scrapers are the bowl, the apron, the ejector (all hydraulically operated), and the cutting edge. Wheel-tractor scrapers are particularly useful for moving earth considerable distances while crawler-tractors are more suited for shorter distances. Both types are capable of discharging material in a spreading action. Heaped capacities of tractor-pulled scrapers range from 8 to 30 cubic metres and heaped capacities of motorised scrapers range from 15 to 50 cubic metres. Scrapers can also be classified into:

1. Single engine
2. Three-axle

3. All-wheel drive
4. Tandem-powered
5. Elevating
6. Push-pull
7. Multi-bowl, multi-engine

Scrapers are most effective for operations where loose material must be picked up and transported such as in stripping of top soil, contour grading and cutting and filling. Scraper productivity can be increased by ripping the material and, in some cases, by prewetting the material and loading down grade. Figure 1 shows types of scrapers commonly used in surface coal mines.

3.2 Draglines

Draglines have been used extensively on irrigation projects, in sand and gravel pit and surface mining operations. Figure 2 indicates the variety of dragline applications. Basically, a dragline is a mobile crane with a drag bucket on the hoist line and a drag cable from the bucket to a second drum, [Fig. 3]. There are two types of draglines, crawler-mounted types using diesel-powered generators and walking draglines which are electric-powered. Crawler-mounted draglines can handle buckets with capacities up to 14 m^3 while walking draglines can handle buckets with capacities up to 170 m^3. Draglines can handle a variety of materials, feature relatively low operating costs and can dig above or below grade. They are most efficient when excavating loose, bulk material. An inherent advantage over shovels is that draglines can be operated from outside a pit, thereby resting on solid ground and avoiding problems associated with the bearing capacity of the pit floor. However, draglines cannot readily handle hard material often necessitating extensive ground preparation. Major considerations affecting selection of draglines are their high purchase costs and the potentially long manufacturing and installation times.

3.3 Power Shovels

There are two classes of power shovels, cable (or rope) shovels and hydraulic shovels.

The basic parts of a cable shovel are the boom, the dipper stick, the dipper (or bucket) and the controlling cables. Size of a power shovel is defined by the size of the dipper. Cable shovels can handle dippers with capacities up to 50 cubic metres, making them ideal for loading very large trucks. The digging paths of cable shovels form circular arcs consisting of a combination of hoisting and crowding actions [Fig. 4] which generate high digging forces and allow use of these types of shovels in hard digging conditions. Furthermore, due to their height and reach, cable shovels can work in high benches (maximum cutting height approaching 25 metres) and dump heights up to 12 metres. Figure 5 illustrates the types of applications, including conditions where their use is limited. While cable shovels cannot dig below the floor level, they have been widely accepted due to their relatively low operating costs, high reliability and life expectancy, up to 30 years when

properly maintained.

Development of hydraulic shovels has been very rapid in recent years. Their basic components are illustrated in Figure 6. The machines are crawler-mounted and diesel powered. Although they were originally of smaller capacity, current models with 30 m^3 buckets are challenging the predominance of cable shovels in large operations. This challenge can also be attributed to the higher speed of travel of hydraulic shovels compared to cable shovels. Hydraulic shovels can operate to maximum heights of 15 m. maximum depths of 6 m. and can reach up 9 m. to dump. Their design allovs a range of bucket orientations with respect to the cutting face, enabling their use to dig above and below floor level and their use as a backhoe. Backhoes can be particularly useful in mines with poor ground conditions. When this flexibility is combined with the wrist action [Fig. 7], it results in very high breakout forces, permitting use of such machines in difficult digging conditions. Hydraulic shovels have been used successfully in thin seam operations and in loading consolidated and sometimes unblasted material.

3.4 Front End Loaders

The front-end loader (F.E.Ldr.) is a crawler or wheel-tractor unit with a hydraulically-actuated front-mounted bucket, [Fig. 8]. The machine is designed to dig earth or granular material and to carry it where necessary, and dump it from a height. Buckets sizes range from 0.25 to 24 cubic metres (heaped) capacity, mining loaders commonly using buckets of 5 cubic metres and higher. When it is necessary to work on stockpiles or dig in loose soils, wheel-tractor loaders are used, while crawler-based units are used when higher traction, hence greater digging forces are required. Wheel-tractors are more mobile and easier to manoeuver. F.E. Loaders are capable of speeds up to 45km/hr. F.E Loaders are widely used in the construction and mining industries, common applications include:

loading-hauling,
excavation of foundations,
loading and/or transporting ore, and
road maintenance.

Popularity of F.E. Loaders is based on their ability to selectively dig material, their good blending capabilities and their maneuverability. However, they cannot handle hard materials without ground preparation and operating and maintenance costs can be adversely influenced by tire replacement costs.

3.5 Bucket Wheel Excavators

The bucket wheel excavator (BWE), used in continuous mining operations, can be a very productive, although elaborate, excavating unit. Figure 9 illustrates the major components of such continuous surface mining systems. Golosinski and Singhal (1987) revieved the performance of the BWE and have identified the following advantages:

(a) The equipment is physically smaller than conventional equipment required to perform the same task.

(b) Instantaneous power requirements are small with distinct peaks in power demand absent.

(c) BWE can operate efficiently through a wide range of mining geometries and can operate on, below or above the transportation level.

(d) Material excavated is of small size permitting its direct loading on conveyors without further treatment.

(e) The operation lends itself to complete automation, with the associated economic benefits.

BWEs have proven particularly useful for removal of soil overburden and broken ores. However, they have difficulty handling hard material and rock formations, often requiring extensive ground preparation. They also require a higher capital investment than other excavating equipment.

4.0 EXCAVATING EQUIPMENT SELECTION PROCESS

Figure 10 illustrates the main factors influencing selection of excavating equipment. A more detailed description of the different modules can be found in Scoble et al (1987). Atkinson (1971) and Richardson (1970) have also discussed the problems concerning equipment selection. This report concerns the geotechnical and equipment considerations which form the foundations of the knowledge based system.

4.1 Geotechnical Considerations

The ability of excavating machines to perform with or without some form of ground preparation (ripping or blasting) is a fundamental consideration in their selection. Thus, the knowledge-based system for equipment selection focuses initially on ground characterization and its effect on equipment applicability and performance. In order to apply experience obtained from various sites, rock classification schemes have been developed (Table 1). An important task in their development is the choice of parameters which can be grouped as primary and secondary geotechnical characteristics. The prototype knowledge-based system relies on rules which define the primary excavation properties from geotechnical information about the site provided by the user. While it is possible to define and implement rules based on secondary characteristics, this will be undertaken later when more reliable field data are obtained. Mine and construction site visits are planned to collect such data.

4.2 Primary Geotechnical Characteristics

4.2.1 Weathering

Weathering of rocks occurs, under the direct influence of the hydrosphere and atmosphere, as a result of their instability in environments different from those in which they were formed. Weathering can lead to significant reductions in the strength of the rock mass, influencing the diggability of the material, [Fig. 11], (Dearman 1974). Weathering is often a localised condition exhibiting significant lateral and vertical variation in intensity. This necessitates subdivision of the ground stratigraphic horizons into zones of different degrees of weathering. The capability of a piece of equipment to excavate weathered horizons, probably near the surface, does not imply that it can be used efficiently in deeper and less weathered rock mass horizons.

4.2.2 Mechanical properties of rock

The strength of intact rock and rock discontinuities is estimated both by in situ and laboratory methods. Discontinuities define weakness planes along which it is easier to dig. Another important consideration is the nature of the failure mechanism. Rock can fail in tension and compression. Dubbe (1974) demonstrated in field and model studies that high tensile stresses are concentrated in the rock around the tip of the ripper. Thus, rock diggability may affected more by tensile rather than compressive strength. While direct techniques for determining rock tensile strength have been proposed, (International Society of Rock Mechanics, ISRM 1981), it is more common to employ indirect testing methods, principally the Brazilian, (ISRM 1981), and Point-Load tests, (ISRM 1985). The test arrangement for the point load test is shown in Figure 12 and it has been proposed as a standard test for rock classification by Coleman and Fitzhardinge (1979). This test provides strength values both parallel and perpendicular to bedding or other structures thus accounting for strength anisotropy. Brook (1985) has suggested that it can also be used with relatively unprepared rock lumps. Furthermore the equipment is portable and relatively inexpensive to use.

4.2.3 Bedding spacing

This geological parameter, a characteristic of sedimentary rocks, defines the average thickness of bedding planes which are surfaces parallel to the surface of deposition. Bedding planes can appear as discontinuous planes of weakness (i.e. shale) or in the form of change in colour and/or grain size, such as in sandstones.

4.2.4 Joint properties

The number of joints and their spacing in the rock mass are important parameters in most surface excavation classification schemes (Table 1) because they affect the mechanical behaviour and appearance of the rock mass [Fig. 13]. On the other hand, while the degree of roughness of

joints, is of primary importance in slope stability estimations, it exerts a smaller influence on the excavation process. The ISRM (1981) has suggested ways by which the joint characteristics can be measured.

4.2.5 Block size

Block size may be a more useful parameter for excavation classification purposes than the individual joint properties. The discontinuity orientation and spacing dictate the dimensions and shape of blocks in the rock mass. The block size and shape will dictate the ease of excavation of a rock mass and will also influence the realization of production goals. Different shapes of rock blocks are shown in Figure 14. Accurate determination of block size in a rock mass has been impeded by its three-dimensional nature while investigations are usually two-dimensional. Franklin (1974) has recommended the use of a fracture spacing index If, defined as the average diameter of a "typical block". In practice, If is estimated by visually selecting typical sizes of core or outcrop material and recording their average dimension. It is also expedient to determine a range of If values for typical "largest" and "smallest" blocks. The ISRM Commission on Testing Methods (IRSM 1981) suggested the use of the volumetric joint count (Jv) as an indication of block size. Jv is defined as the sum of the number of joints per metre for each joint set present. A correlation between Jv and corresponding block size is presented in Table 2.

Kirsten (1982) highlighted the effect of block size on the effort to excavate a rock mass. His classification scheme incorporated a dimensionless factor (RQD/Jn), where RQD is rock quality designation (Deere 1963) and Jn is the joint set number (i.e. number of joints). A disadvantage of this approach is that the RQD value is greatly influenced by the direction in which measurements are taken. To overcome the limitations of RQD as an adequate measure of rock mass quality, Kazi and Sen (1985) suggested the use of a volumetric RQD that can be correlated to the volume of a matrix block and the number of matrix blocks per cubic metre. The knowledge-based system described in this report relies on a definition of the block size based on the volumetric joint count Jv of the rock mass.

4.2.6 Relative ground structure

The importance of the orientation of structural discontinuities has already been mentioned with respect to block size definition. Weaver (1975) recognized that the strike and dip orientation of discontinuities and bedding planes may assist or hinder the excavating process. Kirsten (1982) investigated the kinematic possibility of dislodging a block as a function of the relative orientation of the joint sets, the direction of attack relative to the ground surface and the amount of work required. He suggested quantitative values for the degree of assistance provided by the orientation of structural discontinuities. A relative ground structure rating, (Js), based on Kirsten's methodology, has been integrated into the excavating index rating scheme proposed in the next section. It is felt that this approach can be of particular significance in equipment selection in stratified ground.

4.3 Secondary Geotechnical Parameters

4.3.1 Seismic velocity

Seismic velocity has been used to predict ease of excavation. Church (1960) reported one of the first rippability charts prepared by Fahnestock in 1959 for the Caterpillar Company, which provides such charts for a range of its equipment, [Fig. 15]. In surface seismic refraction, the time taken by compressional waves to travel through different subsurface materials is recorded. The velocity of the seismic wave is a function of rock hardness, stratification, degree of fracturing, and extent of weathering as well as confining stress. However, Stacey (1976) has shown that compressional wave recordings are less sensitive to the presence of discontinuities than shear waves. Their continued popularity is mainly based on their ease of detection arising from relatively higher velocity. While the accuracy of seismic velocity data for rippability prediction has been questioned (Scoble et al. 1987), (Kirsten 1982), (Dubbe 1974) the method is still widely used. The main limitations of the seismic velocity technique as a means of determining ease of excavation are:

(a) each ground layer must be underlain by one of lower velocity.

(b) the presence of non-rippable large boulders cannot be detected if present within easily rippable material, (Smith 1987).

(c) geological variations not relevant to rippability may lead to seismic velocity fluctuations Kirsten (1982).

(d) no distinction is made of variations in the ground water table and/or degree of saturation of the material, (Turk and Dearman 1986).

(e) seismic velocity is a rock characterization technique that does not necessarily provide an accurate estimate of the rock fracture strength, (Dubbe 1974).

Given the current state of development of seismic techniques, it does not seem appropriate to include them as an integral part of an excavation classification scheme, at this time.

4.3.2 Trafficability

While much attention is paid to the excavating capabilities of equipment, trafficability problems are sometimes overlooked. High quality mine access and haul roads are necessary to ensure maximum production, reduced operating costs and a safer working environment, (Atkinson and Walton 1983)(Kaufman and Ault 1977). Atkinson and Walton (1983) have dealt with haulage road design. The California Bearing Ratio (CBR) test has been used in mines for evaluating subbase thickness requirements in relation to subbase characteristics. Jonah (1985) has shown that trafficability is a function of ground saturation level. In a

test pit at the Syncrude mine he observed that trafficability ranged from excellent for dry conditions to problematic when the surface was exposed to water, hence requiring continuing attendance. In some climatic conditions, mine production can be severely affected during periods of heavy rainfall due to traction loss on mine roads.

4.3.3 Ground bearing pressure

The use of heavy excavating equipment necessitates verification that the ground is capable of supporting the weight of the equipment. Gleghorn and Clark (1985) and Jonah (1985) report on in situ studies to determine ground bearing capacity by using pressure cells. They found that the maximum dynamic loading pressure, exerted when digging, was 3.5 times the average static load exerted by the machine. These considerations also strongly influence the determination of an optimum excavating strategy.

4.3.4 Abrasivity and stickiness

The abrasivity of rock depends on its mineralogical composition and the bond strength between the mineral grains. The methods suggested by ISRM (1981) for determining the abrasivity of rock, include the Los Angeles Test, the Schmidt Rebound hardness and the Shore Scleroscope. Adler and Krishnan (1983) recommend the use of silica content as an indication of the degree of abrasivity. Abrasivity is of particular importance in continuous surface mining operations. Subramanian (1986) recounted its effects at the Neyveli Lignite Mine in India where studies led to the adoption of the BWE as the main excavating equipment. Although the excavators were designed for the abrasive sandstone at Neyveli, operational goals were never achieved. The extreme abrasivity of the ground initially resulted in a bucket tooth life of 3 hours. However, subsequent testing and modifications succeeded in prolonging the life to 300 hours. In soft and argillaceous rocks, the presence of water may render the broken material extremely difficult to convey and dump. This problem can be acute in BWE operations where bucket and conveyor cleaning may be required to maintain productivity.

5.0 A NEW APPROACH TO EXCAVATION EQUIPMENT SELECTION

The problem of excavating equipment selection has been tackled with the help of more traditional computerised techniques, such as linear and dynamic programming. A common premise of these methods is the availability of precise and abundant data. However these numerical techniques are limited in their ability to account for the influence of less formalised and less clearly defined factors. Experience may often provide a better basis for evaluating equipment suitability. Knowledge based or expert system technology provides a means of dealing with problems of ill-defined structure and scarce or incomplete data.

5.1 Knowledge-Based System For Selection of Excavation Equipment

Knowledge-based or expert systems are computer programs utilising artificial intelligence techniques and methodology. Their distinctive

feature is the ability to reason and reach conclusions in very specific domains. Expert system architecture has been extensively reviewed (e.g. Jackson 1983). The main components of an expert system are the knowledge base and the inference engine. The programming activity involves selection or development of a reasoning tool or inference engine and creation of the knowledge base used by that tool. In recent years, many expert system development tools or "shells" have been created. These range from more sophisticated research-oriented tools such as "ART" (Inference Corp.) to mid-range systems such as "GURU" (Micro Data Base Systems Corp.) to smaller and less expensive systems such as "MicroExpert" (McGraw Hill Inc). Gevanter (1987) reviewed several commercially available expert system shells. Greater capabilities are usually provided by the more complex systems which also require more powerful computing resources.

The main goal of this project was to develop a system that could be implemented on microcomputers of the type normally used at minesites. This consideration led to development of an NRC/DME inference engine. This rule-based, backward-chaining inference engine was developed for an IBM AT microcomputer using Borland's Turbo Prolog (Moran, 1988). The engine could be modified and expanded to accommodate specific requirements of the excavation equipment selection system, without cluttering the shell with unnecessary options. Appendix A lists the available options of the expert system. During the past year, the inference engine has been modified and enhanced with little change in memory requirements. The process of refining the rule base is a continuous one and involves the application of the knowledge-based expert system to specific case studies. The prototype system has been tested in coal mine environments. One problem is the limited amount of appropriate data available from published sources. The next stage involves further field application of the ES whereby it will be refined as more knowledge is acquired. Furthermore, the equipment data base will be updated to account for new equipment developments. The long term objective of the Systems Laboratory is the integration of geotechnical, production and environmental considerations into a more comprehensive equipment selection system. This will form part of a so-called "Decision Support System for Surface Mining" which will focus on tactical planning (Nenonen et al. 1988).

5.2 Development of the Knowledge Base (KB)

A review of geotechnical parameters relevant to excavation and transportation has already been presented. Various researchers have used some of these parameters to construct rock classification schemes. Table 1 illustrates the different classification schemes with their pertinent parameters.

In development of the expert system, two knowledge bases were created to capture the geotechnical information. These knowledge bases were created using Turbo PROLOG and are compatible with the NRC/DME inference engine developed in the Systems Laboratory (Moran 1988). The engine was modified "in-house" to perform the tasks required by the excavation equipment expert system, including the introduction of certainty factors

and the associated algebra.

The first knowledge base constructed (Digindex) uses the concept of a diggability index (D.I.) as proposed in the work of Scoble and Muftuoglou (1984). A rating system was used (Table 3) to determine the D.I. which was in turn used to select the appropriate excavating equipment. The second knowledge base (Excindex) uses a more complete set of geotechnically-based rules. First, primary and secondary ground characteristics are evaluated. The primary properties are the Point Load Strength and Block Size which influence the ease of excavation and transportation of a rock mass. Weathering and orientation of any discontinuities relative to the ground and loading/ripping direction, will modify the excavation index ratings. For particular equipment such as the BWE, consideration should be given to abrasivity, while seismic velocity can best be used as an independent test of rippability for comparative purposes. Trafficability and ground bearing pressure should also be verified once preliminary equipment selection is made.

The excavation index, EI is determined as follows:

$$EI = (Is + Bs)W.Js$$

where

Is = Point Load Strength Index

Bs = Block size Index

W = Weathering Index

Js = Relative Ground Structure Index

The values assigned to the different parameters are shown in Table 4. Appendix B provides a partial listing of the two knowledge bases.

5.3 The Inference Engine

Moran (1988) has prepared a user's guide for the inference engine (IE). In this section, a brief outline of the capabilities of the IE are presented. The engine has been implemented in Turbo PROLOG which, when linked with the knowledge base, constitutes the Expert System. The IE includes an editor to facilitate addition or deletion of rules in the knowledge base and a listing of these rules. If requested, the expert system can display the reasoning it uses to reach its conclusions and recommendations. The IE uses confidence factors assigned by the user to inputs and to the rules to derive certainty factors for the conclusions. The IE can use any of the following four certainty factor algebraic operations:

- minimum,
- product,
- average, and
- Bonczek-Eagin

Use of certainty factors in expert or knowledge-based systems is a relatively new development. Introduction of the above certainty factor operations provides a state-of-the-art option to the knowledge based expert system.

6.0 CONCLUSIONS

A prototype of a knowledge-based expert system has been developed to select the most suitable types of surface excavating equipment for a range of geological environments. Such a system can assist mining operators and excavation contractors and developers. As it stands, the system uses two excavation engineering classification systems and an equipment data base and forms the initial part of a more comprehensive system being developed which will also account for production and environmental factors. An example of its implementation is shown in Appendix C.

7.0 RECCOMENDATIONS FOR SUBSEQUENT WORK

A subsequent stage in this project will be the expansion of the system's existing knowledge bases by incorporating the wide range of equipment specifications, already collected. This stage will include determination of additional rules dealing with digging mechanics and equipment characteristics as well as project specifics. Eventually, the different modules developed in the Systems Laboratory should be integrated into a tool for the mining industry. Finally, to expand the usefulness of the prototype knowledge-based system, it should be enhanced to assist not only in equipment selection but also in the prediction of equipment performance, an on going concern in the mining industry.

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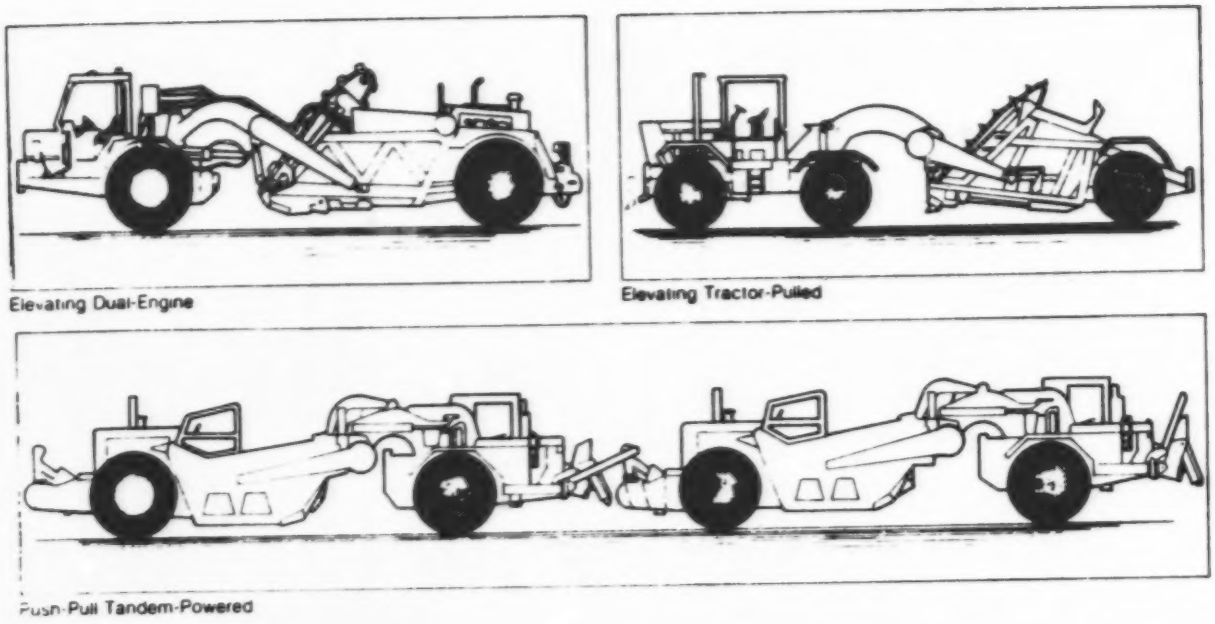


Figure 1. Popular types of scrapers used in surface coal mines (Anonymous 1980b, 1981)

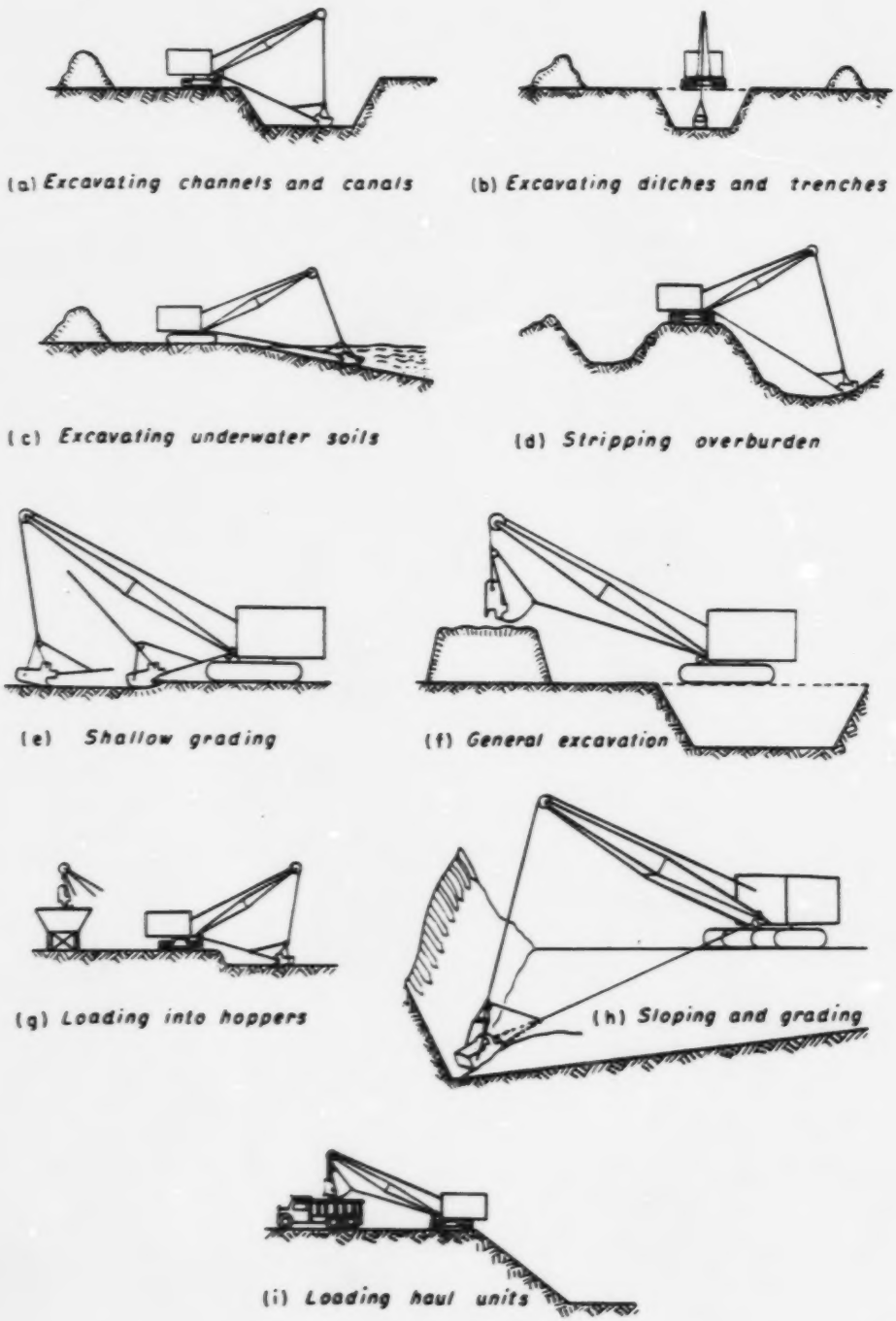


Figure 2. Uses of the dragline (Carson 1980).

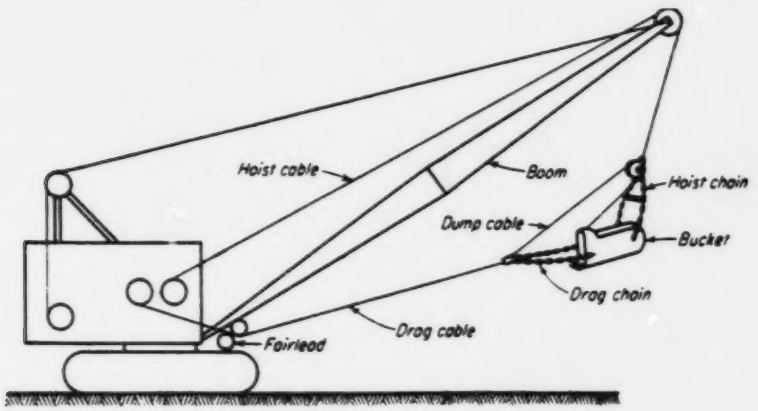


Figure 3. Basic parts of a dragline (Peurifoy 1979).

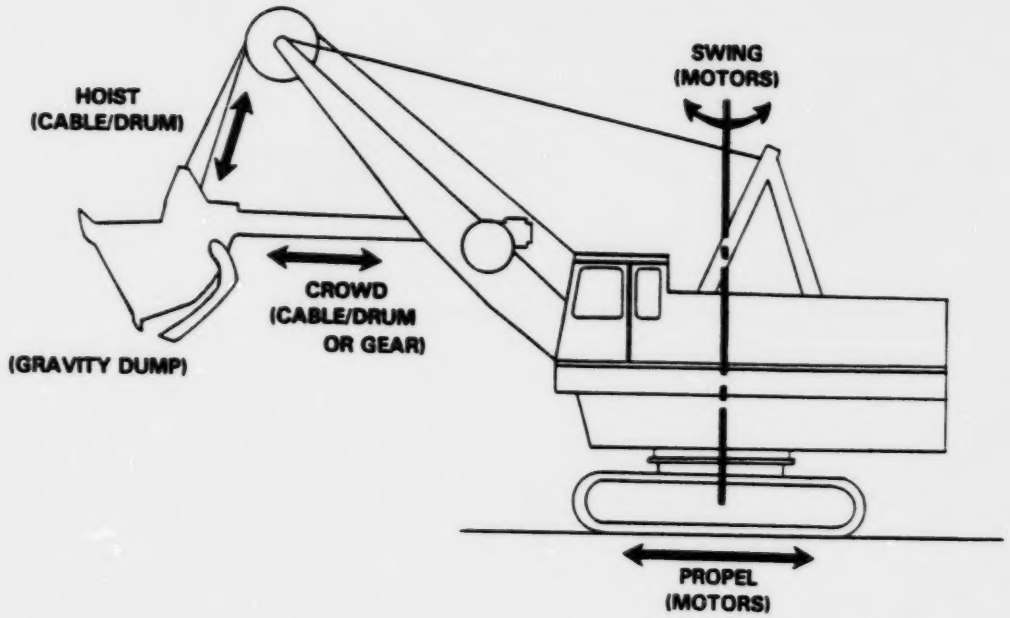


Figure 4. Shovel powered functions (Martin et al. 1982).

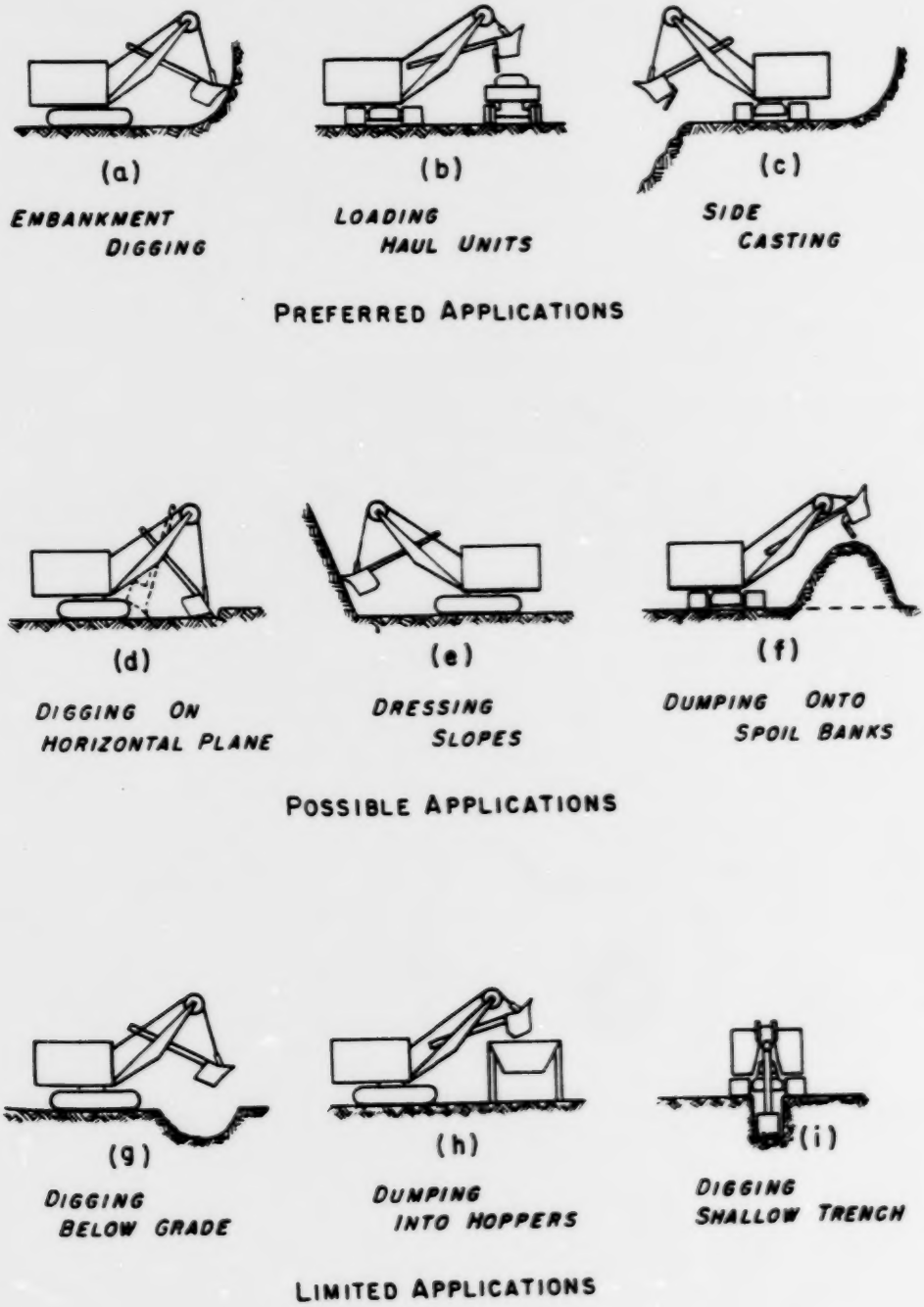


Figure 5. Types of cable shovel applications (Carson 1980).

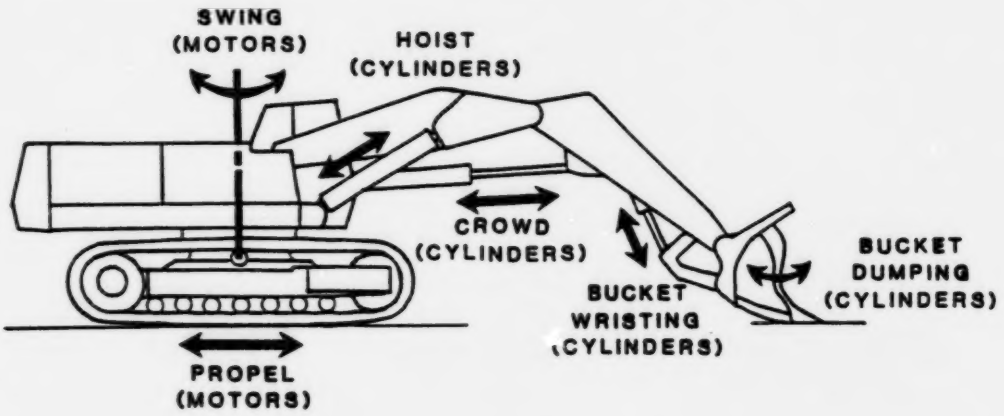


Figure 6. Hydraulic shovel powered functions (Martin et al. 1982).

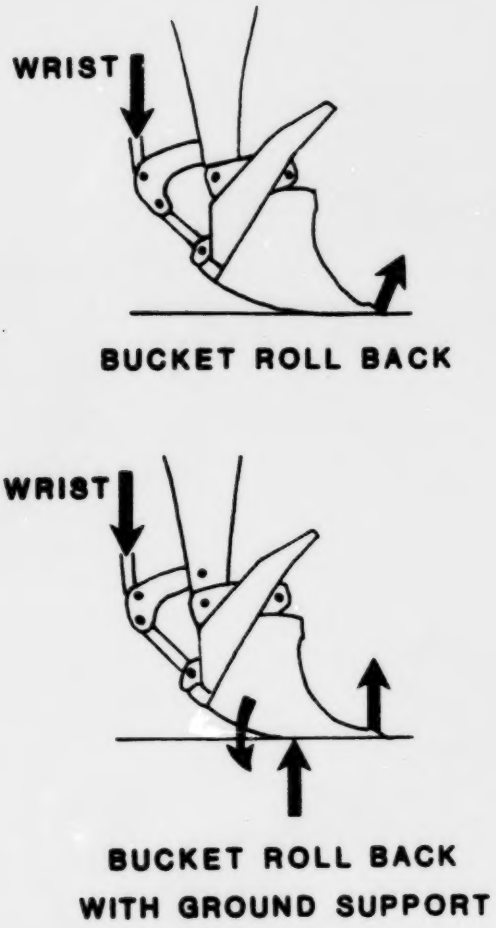


Figure 7. Hydraulic shovel digging forces (Martin et al. 1982).

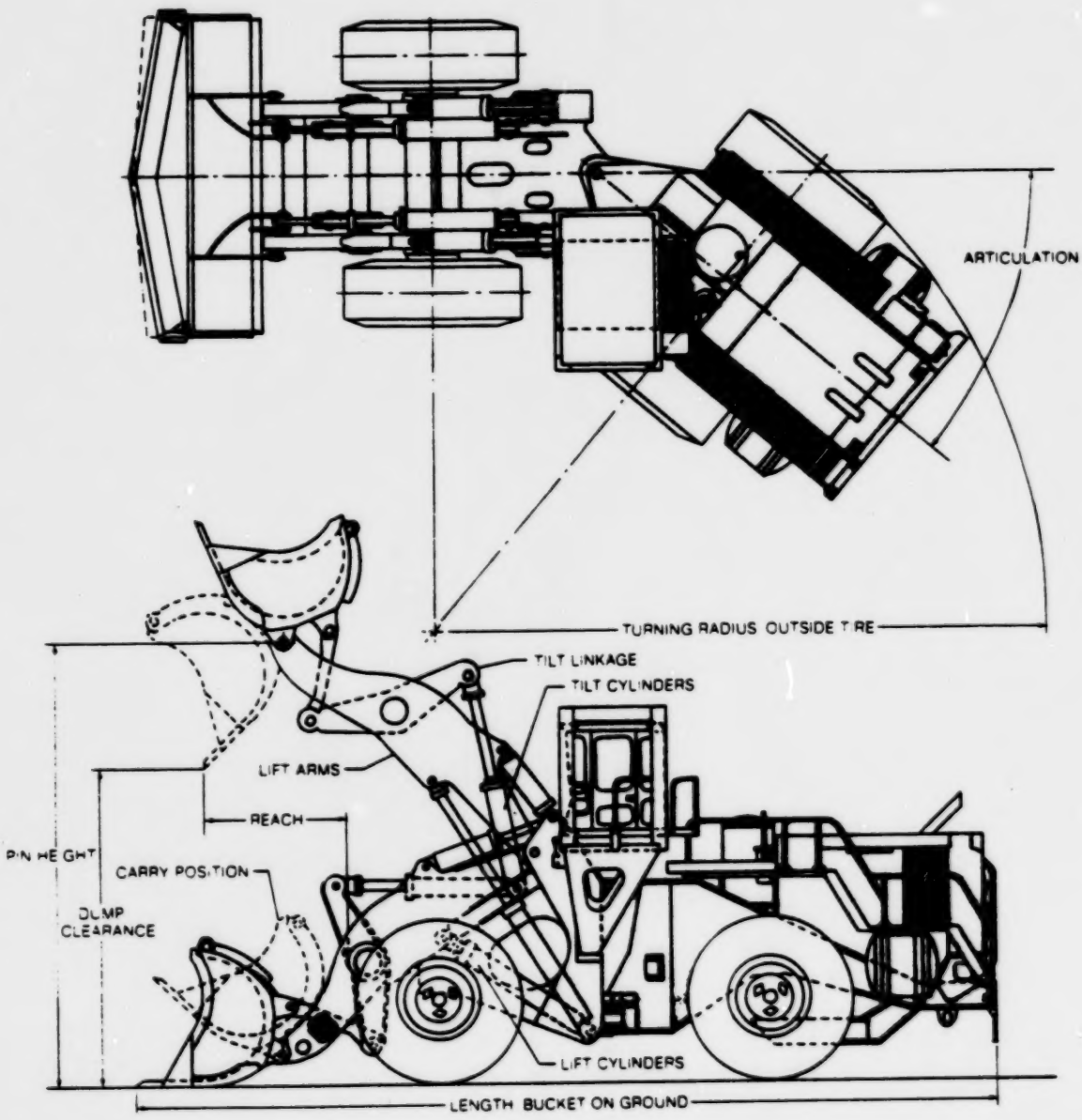


Figure 8. Front-end loader (Anonymous, 1980b).

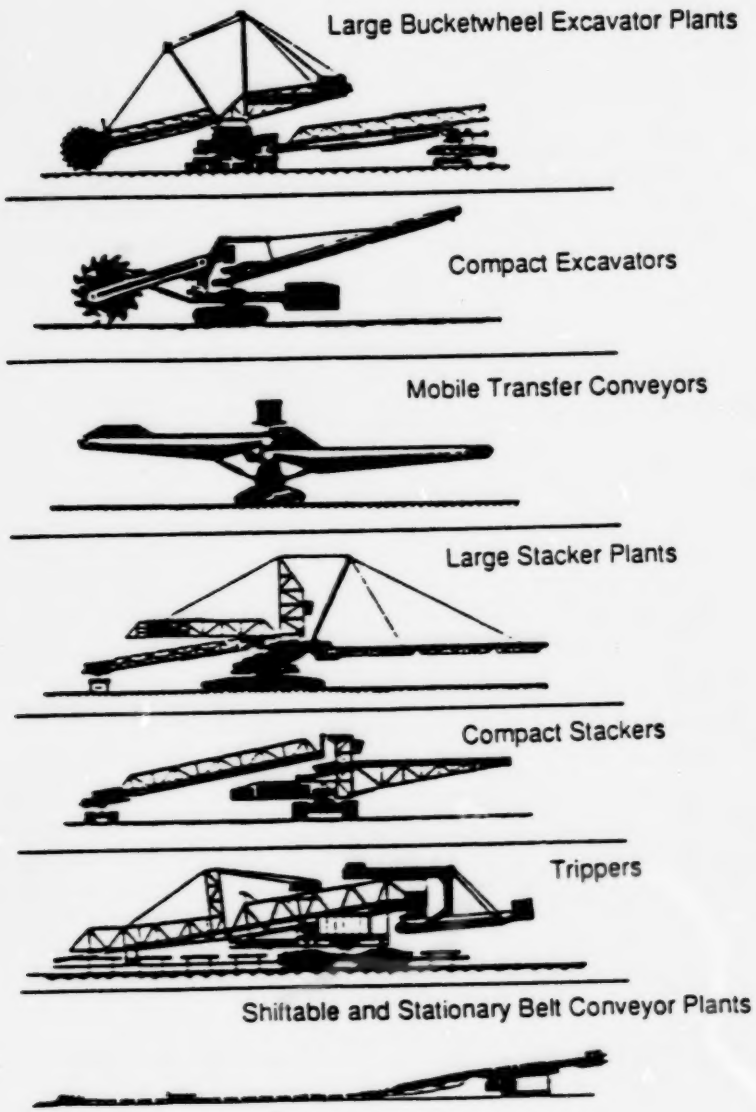


Figure 9. Major components of a continuous surface mining system (Golosinski and Singhal 1987).

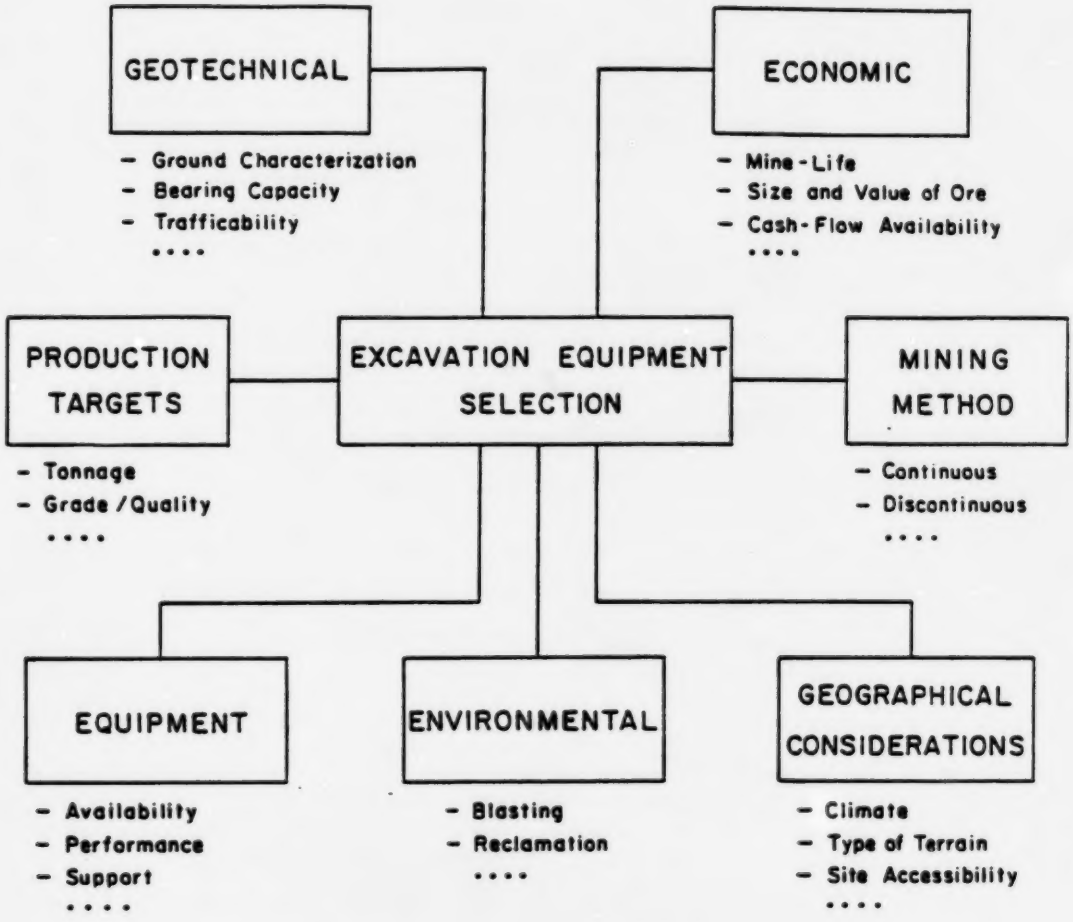


Figure 10. Factors contributing to excavation equipment selection.

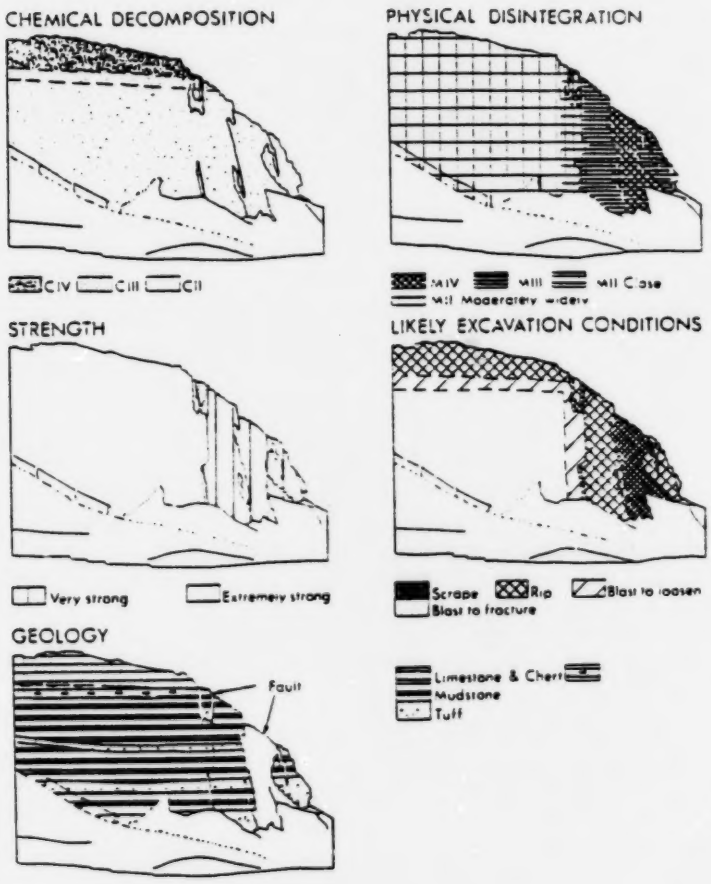


Figure 11. Weathering stages and engineering appraisal of a quarry face (Dearman 1974).

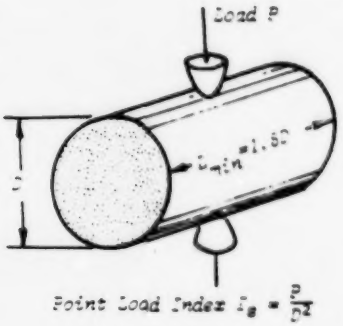
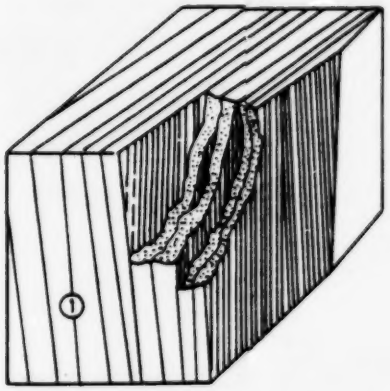


Figure 12. Test arrangement for point load test (Hoek and Bray 1979).



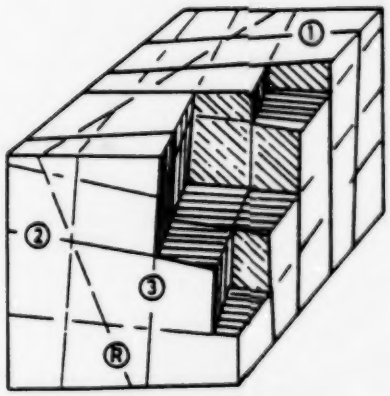


Figure 13. Examples of the type of influence the number of joint sets exert on the mechanical behaviour and appearance of a rock mass (ISRM 1981).

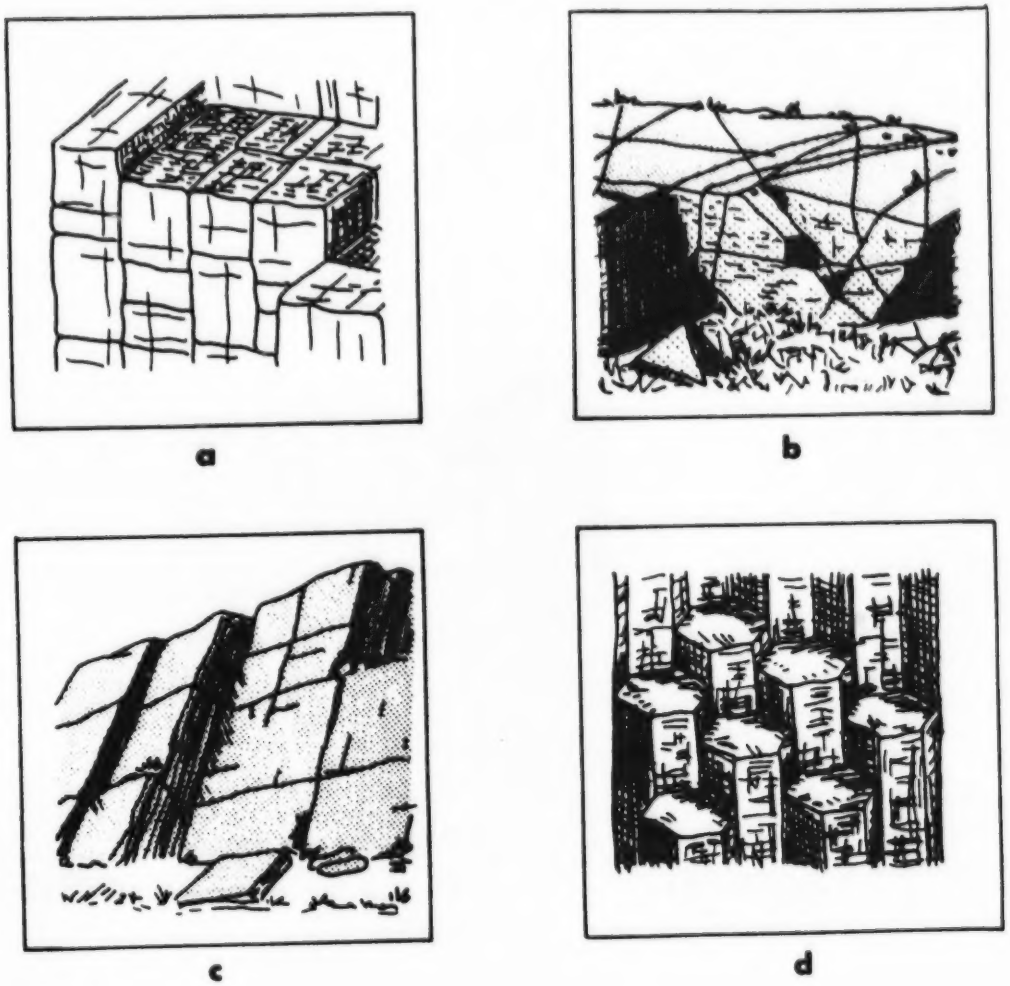
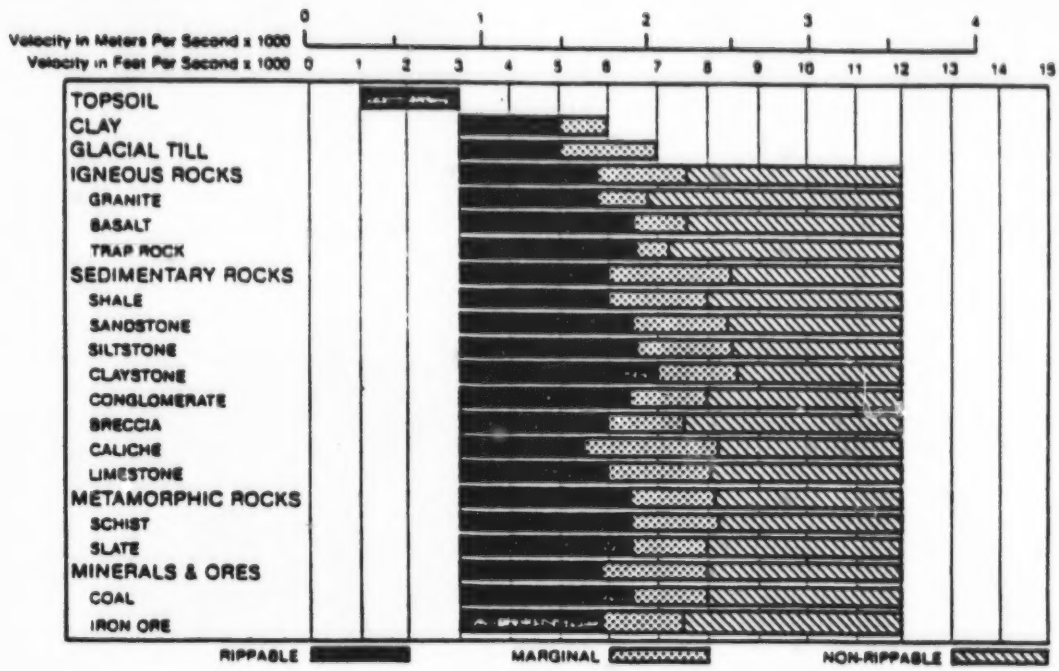


Figure 14. Sketches of rock masses illustrating (a) blocky, (b) irregular, (c) tabular and (d) columnar block shapes (ISRM 1981).



CATERPILLAR D8 RIPPER PERFORMANCE

Figure 15. Rippability charts (Anonomous 1980b)

Table 1

Rock Classification Schemes for Excavating Purposes

Classification Components	Scoble & Muftuoglu (1984)	Weaver (1975)	Kirsten (1982)	Singh et al (1986)	Smith (1986)	Franklin et al (1971)	Read et al (1980)	Scoble et al (1987)
1. Uniaxial Comp. Strength	X	X	X		X	X		
2. Point Load Strength	X			X		X	X	X
3. Tensile Strength				X				
4. Number of Joint Sets			X					
5. RQD			X					
6. Volumetric Joint Count			X					X
7. Joint Roughness			X					
8. Joint Alteration			X					
9. Joint Orientation		X	X		X		X	X
10. Bedding Spacing	X							
11. Joint Spacing	X	X	X	X	X	X	X	
12. Joint Continuity		X			X		X	
13. Joint Gouge		X			X		X	
14. Weathering	X	X		X	X		X	X
15. Seismic Velocity		X		X			X	
16. Abrasivity				X				

Table 2

Jv and Block Size (ISRM 1981)

Description	Jv (joints/m3)
Very large blocks	1
Large blocks	1 - 3
Medium-sized blocks	3 - 10
Small blocks	10 - 30
Very small blocks	30

Table 3

Diggability Index Rating Method

Class	I	II	III	IV	V
Weathering	Completely	Highly	Moderately	Slightly	Unweathered
Rating (W)	<0	5	15	20	25
Strength (U>C>) (MPa)	<20	20-40	40-60	60-100	>100
Is (50)	<0.5	0.5-1.5	1.5-2.0	2.0-3.5	>3.5
Rating (S)	0	10	15	20	25
Joint Spacing (m)	<0.3	0.3-0.6	0.6-1.5	1.5-2.0	>2
Rating (J)	5	15	30	45	50
Bedding Spacing (m)	<0.1	0.1-0.3	0.3-0.6	0.6-1.5	>1.5
Rating (B)	0	5	10	20	30

Table 4

Excavating Index Rating Scheme

Class	I	II	III	IV	V
Is (50) (MPa)	0.50	0.5 - 1.5	1.5 - 2.0	2 - 3.5	3.5
Rating (Is)	0	10	15	20	25
Block Size Jv (joint/m3)	30	10 - 30	3 - 10	1 - 3	1.0
Rating (Bs)	5	15	30	45	50
Weathering	Completely	Highly	Moderately	Slightly	Unweathered
Rating (W)	0.6	0.7	0.8	0.9	1.0
Relative Ground Structure	V.favour--able	Favour--able	Slightly un--favourable	Unfavour--able	Very unfavour--able
Rating (Js)	0.5	0.7	1.0	1.3	1.5

APPENDIX A

LIST OF KNOWLEDGE BASED EXPERT SYSTEM'S COMMANDS

go : Start of consultation.
list fact [base] : Displays the list of facts.
list rule [<rule#>] : Displays the rules from Knowledge Base.
list attribute : Displays all attributes.
list conclusions : Displays the conclusions of the last consultation.
add fact <att name> is <value> : Adds a fact to Knowledge Base.
delete fact <attribute> : Deletes a fact from Knowledge Base.
delete rule <n> : Deletes a rule from Knowledge Base.
write fact [base] : Writes the list of facts to a file.
write rule [<rule #>] : Writes the rules to a file.
write attribute : Writes all attributes to a file.
how <attribute> : Explains how a fact was inferred.
why : Justifies the validity of the question.
talk : Prints a trace of rule evaluation.
quiet : Stops the trace of rule evaluation.
edit <KB> : Edits Knowledge Base and updates working storage.
read <KB> : Reads Knowledge Base into working storage.
exit : Ends consultation session.

APPENDIX B

EXCAVATON AND DIGGABILITY KNOWLEDGE BASE

```
/*************************************************************************/
/*                  Ease of Excavation Knowledge Base.                   */
/*                                                                       */
/*     This is a knowledge base intended to be used with the GIEES       */
/*     Expert System Shell. Its purpose is to characterize the rock      */
/*     mass horizons and subsequently select the optimum excavating      */
/*     equipment for the prevailing geotechnical conditions.             */
/*                                                                       */
/*    *     *     *     *     *     *     *     *     *     *     *      */
/*                                                                       */
/*      Version 1.0                          J. Hadjigeorgiou            */
/*      August 1987                          S. Moran                    */
/*                                                                       */
/*                                                                       */
/*************************************************************************/

/*************************************************************************/
/*                                                                       */
/*  The main goal to be infered is determination of the Excavating       */
/*  Index Rating. The development of the EI rating has been outlined     */
/*  in a paper by Scoble, Hadjigeorgiou and Nenonen presented at the     */
/*  40th Canadien Geotechnical Conference.                               */
/*                                                                       */
*/
/*************************************************************************/

giees_goal("weathering_rating")
    .
    .
    .

/*************************************************************************/
/* The name of the Knowledge base is Ease of Excavation                  */
/*************************************************************************/

kb_name("Expert System")

/*************************************************************************/
/*                                                                       */
/*  The definitions used are of the "boolean"  and "scale" nature .      */
/*************************************************************************/

type("boolean",str_list(["true","false"]))
```

```
/*************************************************************************/
/*                                                                       */
/*  List of Attributes. These should be constructed by including the     */
/*  following parameters :                                               */
/*  a. Attribute number.                                                 */
/*  b. Abreviated attribute name.                                        */
/*  c. Type (i.e. integer, real, string).                                */
/*  d. Full attribute name.                                              */
/*  e. Units if applicable.                                              */
/*                                                                       */
/*************************************************************************/

es_attribute(2101,"degree_weathering","string","degree of weathering",
" ")
        .
        .
        .

es_attribute(9999,"EI_rating","real","excavation index rating"," ")

attribute_definition(4101,["Block size is defined as volumetric joint
count per cubic metre."])



/*************************************************************************/
/*                                                                       */
/*   Legal values. These are the only acceptable answers for the ES.     */
/*   The system will not read mispellings. Legal values are declared     */
/*   by :                                                                */
/*                                                                       */
/*   a. Attribute number.                                                */
/*   b. Acceptable answers.                                              */
/*                                                                       */
/*************************************************************************/

legal_values(2101,str_list(["completely","highly","moderately",
"slightly","unweathered"]))
      .
      .
      .

legal_values(9998,real_list([0.0,400.0]))


askable([2101,3101,4101,5101])
```

```
/*************************************************************************/
/*                                                                       */
/*   Definition of rules :                                               */
/*   a. Rule number.                                                     */
/*   b. Priority number.                                                 */
/*                                                                       */
/*************************************************************************/


rule(1,0)
      .
      .
      .

rule(21,0)


/*************************************************************************/
/*                                                                       */
/*   Declaration of the defining conditions :                            */
/*   a. Rule number.                                                     */
/*   b. Attribute number.                                                */
/*   c. Operator.                                                        */
/*   d. Value.                                                           */
/*                                                                       */
/*************************************************************************/

condition(1,2101,"equal",str("completely"))
    .
    .
    .
condition(21,3102,"has_value",nil)
condition(21,4102,"has_value",nil)
condition(21,5102,"has_value",nil)


/*************************************************************************/
/*                                                                       */
/*   Declaration of conclusions :                                        */
*/   a. Rule number.                                                     */
/*   b. Attribute number.                                                */
/*   c. Value.                                                           */
/*   d. Confidence factor (ranging from 0 - 100).                        */
/*                                                                       */
/*************************************************************************/
```

```
conclusion(1,2102,rel(0.6),100)
    .
    .
    .
conclusion(21,9999,mul(["TEMP","weathering_rating","ground_rating"]),
100)


/*************************************************************************/
/*                                                                       */
/*                  Diggability Index Knowledge Base                     */
/*                                                                       */
/*    This is a knowledge base intented to  be used with the GIEES       */
/*    Expert System Shell (1987). Its purpose  is to  characterize       */
/*    the rock mass horizons and  subsequently select  the optimum       */
/*    excavating  equipment  for   the   prevailing   geotechnical       */
/*    conditions. In  its present, preliminary, form the Knowledge       */
/*    Base is restricted to primary geotechnical characteristics.        */
/*                                                                       */
/*                                                                       */
/*  *        *        *        *        *        *        *             */
/*                                                                       */
/*     Version 1.0                              J. Hadjigeorgiou         */
/*     August 1987                              S. Moran                 */
/*                                                                       */
/*                                                                       */
/*************************************************************************/

giees_goal("weathering_rating")
    .
    .
    .
giees_goal("shovel_digging_equipment")

/*************************************************************************/
/*                                                                       */
/*                        List of ATTRIBUTES                             */
/*                                                                       */
/*    These should be constructed by including the                       */
/*    following parameters :                                             */
/*                                                                       */
/*    a. Attribute number.                                               */
/*    b. Abreviated attribute name.                                      */
/*    c. Type (i.e. integer, real, string).                              */
/*    d. Full attribute name.                                            */
/*    e. Units,if applicable.                                            */
/*                                                                       */
/*************************************************************************/
```

```
es_attribute(2101,"degree_weathering","string","Degree of Weathering",
" ")
    .
    .
    .
es_attribute(9999,"diggability_index","real","Diggability Index"
," ")

/*************************************************************************/
/*                                                                       */
/*                          LEGAL VALUES                                 */
/*                                                                       */
/*    These are the only acceptable answers for the ES.                  */
/*    The system will not read mispellings. Legal values                 */
/*    are  declared by :                                                 */
/*                                                                       */
/*    a. Attribute number.                                               */
/*    b. Acceptable answers.                                             */
/*                                                                       */
/*************************************************************************/

legal_values(2101,str_list(["completely","highly","moderately"
,"slightly","unweathered"]))
    .
    .
    .
askable([2101,2201,2301,2401])

/*************************************************************************/
/*                                                                       */
/*                    Definition of RULES :                              */
/*                                                                       */
/*      a. Rule number.                                                  */
/*      b. Priority number.                                              */
/*                                                                       */
/*************************************************************************/

/*************************************************************************/
/*                                                                       */
/*                          RULE GUIDE :                                 */
/*                                                                       */
/*     2100   Rules pertaining to weathering                             */
/*     2200   Rules pertaining to bedding spacing                        */
/*     2300   Rules pertaining to joint spacing                          */
/*     2400   Rules pertaining to intact rock strength                   */
/*     2500   Rules pertaining to ease of digging                        */
/*     2600   Rules pertaining to equipment selection                    */
/*     9999   Summation                                                  */
/*                                                                       */
/*************************************************************************/
```

```
rule(2110,0)
    .
    .
    .
rule(9999,0)

/*************************************************************************/
/*                                                                       */
/*          List of conditions pertaining to rules/attributes            */
/*                                                                       */
/*************************************************************************/

/*************************************************************************/
/*                                                                       */
/*           Declaration of the defining CONDITIONS :                    */
/*                                                                       */
/*     a.  Rule number.                                                  */
/*     b.  Attribute number.                                             */
/*     c.  Operator.                                                     */
/*     d.  Value.                                                        */
/*                                                                       */
/*************************************************************************/

condition(2110,2101,"equal",str("completely"))
     .
     .
     .
condition(2670,2501,"equal",str("marginal_without_blasting"))

/*************************************************************************/
/*                            CONCLUSIONS                                */
/*************************************************************************/
/*                Declaration of CONCLUSIONS :                           */
*/                                                                       */
/*     a.  Rule number.                                                  */
/*     b.  Attribute number.                                             */
/*     c.  Value.                                                        */
/*     d.  Confidence factor (ranging from 0 - 100).                     */
/*                                                                       */
/*************************************************************************/

conclusion(2110,2102,int(0),100)
    .
    .
    .
conclusion(2670,2603,str("hydraulic_shovel>10m^3"),100)
```

APPENDIX C

CASE STUDY APPLICATION OF THE KNOWLEDGE-BASED EXPERT SYSTEM

This is an example of a consultation to select the appropriate excavation equipment using the DIGINDEX knowledge base. The "talk" option of the inference engine is used in order to fully display the iteration procedure followed by the inference engine.

```
es
read digindex
talk> go--> Rule #2110 is unknown.
What is the degree of weathering?
Legal values:
             {completely,
              highly,
              moderately,
              slightly,
              unweathered}

What is the degree of weathering? completely 78--> The attribute
"degree_weathering" is "completely". (0-78)
--> The attribute "weathering_rating" is "0". (2110-78)
--> Rule #2110 is true.
--> Rule #2120 is false.
--> Rule #2130 is false.
--> Rule #2140 is false.
--> Rule #2150 is false.
--> Rule #2220 is unknown.
What is the Bedding Spacing (cm)? 56--> The attribute
"bedding_spacing" is "56". (0-100)
--> Rule #2210 is false.
--> Rule #2220 is false.
--> The attribute "bedding_rating" is "10". (2230-100)
--> Rule #2230 is true.
--> Rule #2310 is unknown.
What is the Joint Spacing (cm)? 34 89--> The attribute
"joint_spacing" is "34". (0-89)
--> Rule #2310 is false.
--> The attribute "joint_rating" is "15". (2320-89)
--> Rule #2320 is true.
--> Rule #2330 is false.
--> Rule #2340 is false.
--> Rule #2350 is false.
--> Rule #2410 is unknown.
What is the Intact rock strength (MPa)? 56 90--> The attribute
"intact_strength" is "56". (0-90)
--> Rule #2410 is false.
--> Rule #2420 is false.
--> The attribute "strength_rating" is "15". (2430-90)
--> Rule #2430 is true.
--> Rule #2440 is false.
```

```
--> Rule #2450 is false.
--> The attribute "diggability_index" is "40". (9999-78)
--> Rule #9999 is true.
--> Rule #2510 is false.
--> The attribute "ease_digging" is "easy". (2520-78)
--> Rule #2520 is true.
--> Rule #2530 is false.
--> Rule #2540 is false.
--> Rule #2550 is false.
--> Rule #2560 is false.
--> Rule #2610 is false.
--> The attribute "ripping_equipment" is "ripper_scraper". (2620-
78)
--> The attribute "dragline_equipment" is "dragline > 8c.m.".
(2620-78)
--> The attribute "shovel_digging_equipment" is
"rope_shovel>5c.m.". (2620-78)
--> Rule #2620 is true.
--> Rule #2630 is false.
--> Rule #2640 is false.
--> Rule #2650 is false.
--> Rule #2660 is false.
--> Rule #2670 is false.


****************** Expert System's reccomendation **************

The Weathering rating is 0 (78%)

The Bedding Spacing Index is 10 (100%)

The Joint Spacing Index is 15 (89%)

The Intact Rock Index is 15 (90%)

The Diggability Index is 40 (78%)

The Ease of Digging is easy (78%)

The suitable Ripping Equipment is ripper_scraper (78%)

The suitable Dragline cast is dragline>8c.m. (78%)

The suitable Shovel Digging Equipment is rope_shovel>5c.m. (78%)
```

APPENDIX D

SURFACE EXCAVATION EQUIPMENT: GENERAL SPECIFICATIONS

Scrapers:

Total Flywheel : 150 - 717 hp.
Max. Depth of Cut : 6 - 20 feet.
Max. Width of Cut : 7.5 - 13 feet.
Max. Forward Speed : 24 - 34 mph.
Capacity heaped : 8.5 - 56 cubic yards.
Rated Payload : 26,200 - 104,000 lbs.
Operating Weight : 32,340 - 167,270 lbs.

Crawler mounted draglines :

Horsepower : 550 -2000.
Bucket capacities : 6 - 18 cubic yards.
Operating Weight : 375,000 - 750,000 lbs.
Boom Lengths : 90 -200 feet.
Max. Forward speed : up to 1mph.

Walking Draglines :

Horsepower : 1,000 - 24,000.
Bucket Capacities : 10 - 220 cubic yards.
Operating Weight : 1,000,000 - 30,000,000 lbs.
Boom Lengths : 175 - 375 feet.
Max. Forward speed : 0.15 mph.

Bucket Wheel Excavators :

More than any other surface equipment these are being customised to particular mine conditions, hence the large variations. Martin et al (1982) distinguish BWE into those using :

Large Stripping Wheels :
Wheel Diameters : 21.6 - 38 feet.
Capacity : 2700 - 7600 cu.yd./hr..
Digging Height : 75 - 104 feet.

Medium Size Wheels :
Wheel Diameters : 10 - 25 feet.
Horsepower : 250 -1600.
Capacity : 400 - 3500 cu.yd./hr..
Digging Height : 20 - 50 feet.

Small Fixed Wheels :
Wheel Diameters : 3 - 16 feet.
Horsepower : 200 - 1600.
Capacity : 1000 - 2800 cu.yd./hr..
Digging Height : 0.5 - 12 feet.

Front End Wheel Loaders :

Capacity : 3.5 - 30 cubic yards.
Horsepower : 180 - 1,270.
Max. Dump Clearance : 9 - 19 feet.
Breakout Force : 30,000 - 192,500 lbs.
Turning Radius, Outside tires : 9 - 46 feet.
Max. Forward Speed : up to 30 mph for wheel loaders.

Hydraulic Shovels :

Horsepover : 67 - 1290.
Hydraulic System Pressure : 1900 - 5230.
Operating Weight : 2,420 - 609,000.
Max. Digging Heights : 29 -48 feet.
Max. Digging Depths : 6 - 30 feet.
Max. Dumping heights : 6 - 40 feet.
Max. Reach at dumping : 15 - 32 feet.
Max. Forward Speed : 0.75 - 2 mph.

Cable Shovels :

Capacity : 10 -70 cubic yards.
Horsepover : 1,000 - 5,500.
Peak Hoist motor hp : 500 - 3,900.
Swing motor : 250 - 2,300.
Crowd motor : 250 - 1,065.
Propel motor : 350 -1700.
Working veight : 500,000 - 3,500,000 lbs.
Boom Lengths : 28 - 62 feet.
Max. Dump Height : 20 - 44 feet.

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A KNOWLEDGE-BASED SYSTEM TO AID SELECTION OF EXCAVATING EQUIPMENT

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Prototype, knowledge-based system, geotechnical parameters, excavating equipment, selection, PROLOG

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Describes a PROLOG-based program to assist selection of excavating equipment based on geotechnical properties of the material.

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